



Measurement of CP asymmetry in the $D^0 \rightarrow K_S^0 K_S^0$ decay at Belle

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Abstract

We report a measurement of the time-integrated CP asymmetry in the neutral charm meson decay $D^0 \rightarrow K_S^0 K_S^0$ using 921 fb^{-1} data collected at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The observed asymmetry is

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.17)\%,$$

where the first uncertainty is statistical and the second systematic. This latter uncertainty is dominated by the error of the normalisation channel. The result is consistent with Standard Model expectations and improves the uncertainty with respect to previous measurement of this quantity by more than a factor of three.

Charge-parity violation (CPV) in charmed meson decays has not yet been observed and is predicted to be small [$\mathcal{O}(10^{-3})$] in the Standard Model (SM). Hence, evidence of CPV in charm decays reported by LHCb [1] in $D^0 \rightarrow h^- h^+$ decays, where $h = K, \pi$, took many by surprise and generated a renewed interest in this field as an observation of large CPV in charm decays could hint at New Physics (NP). The difference between the CP asymmetries in $D \rightarrow K^+ K^-$ and $\pi^+ \pi^-$ decays, ΔA_{CP} , was measured to be $(-0.82 \pm 0.21 \pm 0.11)\%$. Recently, LHCb updated their ΔA_{CP} result [2] and the combined ΔA_{CP} value [3] is consistent with no CPV at 6.5% CL. Though there is no current evidence of nonzero asymmetry, CPV in charm decays is investigated in other channels. Singly Cabibbo-suppressed (SCS) decays are of special interest as the possibility of interference with NP amplitudes could lead to larger CPV than predicted by SM. The $D^0 \rightarrow K_S^0 K_S^0$ decay is one such channel [4]. The most recent SM-based analysis obtained a 95% confidence level upper limit of 1.1% for direct CP violation in this decay [5]. The search for CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ has been performed first by the CLEO Collaboration [6] using a data sample of 13.7 fb^{-1} of $e^+ e^-$ collisions at the $\Upsilon(4S)$ with a measured CP asymmetry of $(-23 \pm 19)\%$. Recently, LHCb measured a time-integrated CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ of $(-2.9 \pm 5.2 \pm 2.2)\%$, where the first uncertainty is statistical and the second systematic [7]. The LHCb result is consistent with no CPV, in agreement with SM expectations. The Belle Collaboration has amassed a huge number of $e^+ e^-$ collisions at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, and hence, can significantly improve the measurement.

The analysis is based on a data sample that corresponds to an integrated luminosity of 921 fb^{-1} collected with the Belle detector [8] at the KEKB asymmetric-energy $e^+ e^-$ collider operating at the $\Upsilon(4S)$ resonance, $\Upsilon(4S)$ off-resonance, and $\Upsilon(5S)$ resonance with integrated luminosities 711.0 fb^{-1} , 89.4 fb^{-1} , and 121.4 fb^{-1} , respectively [9]. The Belle detector is a large-solid-angle spectrometer, which includes a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L^0 mesons and identify muons.

In this paper, we measure the time-integrated CP asymmetry (A_{CP}) of the neutral charm meson decays $D^0 \rightarrow K_S^0 K_S^0$. The D^0 mesons are required to originate from the decay $D^{*+} \rightarrow D^0 \pi^+$ in order to provide a tag of the D flavor as well as to suppress combinatorial background. Assuming the total decay width to be same for particles and antiparticles, the time-integrated asymmetry is:

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow K_S^0 K_S^0) - \Gamma(\bar{D}^0 \rightarrow K_S^0 K_S^0)}{\Gamma(D^0 \rightarrow K_S^0 K_S^0) + \Gamma(\bar{D}^0 \rightarrow K_S^0 K_S^0)}, \quad (1)$$

where Γ represents the partial decay width. Here, the A_{CP} term has the following contributions :

$$A_{CP} = A_{CP}^d + A_{CP}^m + A_{CP}^i, \quad (2)$$

where, A_{CP}^d is the direct-CPV contribution or CPV in decay that is decay-mode dependent, A_{CP}^m is the CPV in mixing of D - \bar{D} , and A_{CP}^i is the CPV due to interference between decays with and without mixing. Although the last term depends on the phase difference between mixing and decay, it generally depends on the decay mode. However, the decay phase in D

decays is always close to zero and A_{CP} is almost universal. The asymmetry in the decay width is

$$A_\Gamma = \frac{\tau(D^0 \rightarrow K_S^0 K_S^0) - \tau(\bar{D}^0 \rightarrow K_S^0 K_S^0)}{\tau(D^0 \rightarrow K_S^0 K_S^0) + \tau(\bar{D}^0 \rightarrow K_S^0 K_S^0)} = -(A_{CP}^m + A_{CP}^i) \quad (3)$$

The world average for A_Γ [10], $(-0.056 \pm 0.040)\%$, is consistent with zero [3]. In the SM, indirect CPV ($A_{CP}^m + A_{CP}^i$) is expected to be very small, of the order of 10^{-3} , and is universal for CP eigenstates. Direct CPV is predicted to be small as well. It is expected to be negligible in Cabibbo-favored modes but, in SCS modes, it might plausibly be $\mathcal{O}(10^{-3})$, and could be even larger for the $D^0 \rightarrow K_S^0 K_S^0$ mode, as mentioned in Ref. [5].

The extracted raw asymmetry

$$A_{\text{raw}} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} \quad (4)$$

is given by $A_{\text{raw}} = A_{CP} + A_{FB} + A_\epsilon^\pm$. Here, A_{FB} is the forward-backward production asymmetry, and A_ϵ^\pm is the asymmetry due to different detection efficiencies for positively and negatively charged pions. Both can be eliminated through a relative measurement of A_{CP} , if the charged final-state particles are identical. The chosen normalization mode is $D^0 \rightarrow K_S^0 \pi^0$. We correct for a non-vanishing asymmetry originating from the different strong interaction of K^0 and \bar{K}^0 mesons with nucleons of the detector material, A_ϵ^K , estimated to be -0.11% in Ref. [11], and assign a residual systematic uncertainty of 0.01% . This effect is cancelled in $D^0 \rightarrow K_S^0 K_S^0$ decay since D^0 decays to $K^0 \bar{K}^0$. The CP asymmetry of the signal mode can then be expressed as

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = A_{\text{raw}}(D^0 \rightarrow K_S^0 K_S^0) - A_{\text{raw}}(D^0 \rightarrow K_S^0 \pi^0) + A_{CP}(D^0 \rightarrow K_S^0 \pi^0) + A_\epsilon^K, \quad (5)$$

where $A_{CP}(D^0 \rightarrow K_S^0 \pi^0)$ is the world average of CP asymmetry of the normalization mode: $A_{CP}(D^0 \rightarrow K_S^0 \pi^0) = (-0.20 \pm 0.17)\%$ [12].

The analysis procedure is developed using Monte Carlo (MC) simulation based on EVT-GEN [13] and GEANT3 [14] and includes final-state radiation (FSR) effects simulated by PHOTOS [15]. The selection criteria are optimized using a figure of merit, defined as $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkg}}}$, where N_{sig} (N_{bkg}) represents the number of signal (background) events in a defined signal region. We use a large signal MC sample, about a few hundred times more in size than expected in data. To estimate N_{sig} , we use $\mathcal{B}(D^0 \rightarrow K_S^0 K_S^0) = 1.8 \times 10^{-4}$ [12]. The MC sample used to estimate the background corresponds to a luminosity of six times that of data. The background is scaled by the ratio of the number of events in data and MC in the ΔM sideband, $0.148 \text{ GeV}/c^2 < \Delta M < 0.160 \text{ GeV}/c^2$, where ΔM is the mass difference between the reconstructed D^* and D .

We require a slow pion (π_s) candidate to originate from near the interaction point (IP) by restricting its impact parameters along and perpendicular to the z axis to be less than 3 cm and 1 cm, respectively. The z axis is defined as the direction opposite the e^+ beam. We require that the ratio of the particle identification (PID) likelihood, $\mathcal{L}_\pi/(\mathcal{L}_\pi + \mathcal{L}_K)$, be greater than 0.4. Here, \mathcal{L}_π (\mathcal{L}_K) is the likelihood of a track being a pion (kaon) and is calculated using specific ionization from the CDC, time-of-flight information from the TOF and the number of photoelectrons in the ACC. With the above PID requirement, the pion identification efficiency is above 95% with a kaon misidentification probability below 5%.

K_S^0 mesons are reconstructed from pairs of oppositely charged tracks, treated as pions, using an algorithm based on neural network (NN) [16]. The NN uses the following information: the K_S^0 momentum in the laboratory frame; the distance along the z axis between the

two track helices at their closest approach; the flight length in the $x - y$ plane; the angle between the K_S^0 momentum and the vector joining the K_S^0 decay vertex to the IP; the angle between the pion momentum and the laboratory-frame direction in the K_S^0 rest frame; the distance-of-closest-approach in the $x - y$ plane between the IP and each pion helix; and the pion hit information in the SVD and CDC. We also require that the reconstructed invariant mass be within $15 \text{ MeV}/c^2$ (about four times the resolution) of the nominal K_S^0 mass [12]. We reconstruct neutral pion candidates from pairs of electromagnetic showers in the ECL that are not matched to any charged track. Showers in the barrel (end-cap) region of the ECL must exceed 60 (100) MeV to be considered as a π^0 -daughter candidate. The invariant mass of the π^0 candidate must lie within $25 \text{ MeV}/c^2$ (about four times the resolution) of the known π^0 mass [12]. The π^0 momentum is required to be greater than $640 \text{ MeV}/c$.

To reconstruct the D^0 candidates, we combine two reconstructed K_S^0 (one reconstructed K_S^0 and one π^0 for the normalization mode) and retain the candidates having an invariant mass in the range $1.847 \text{ GeV}/c^2 < M < 1.882 \text{ GeV}/c^2$ ($1.758 \text{ GeV}/c^2 < M < 1.930 \text{ GeV}/c^2$). Finally, π_s is combined with the D^0 to form a D^* candidate, with a requirement on the resulting ΔM to lie in the range $[0.14, 0.16] \text{ GeV}/c^2$. We require that the D^{*+} candidate have a momentum greater than $2.2 \text{ GeV}/c$ in the centre-of-mass frame. This requirement significantly reduces the combinatorial background.

After applying all the selection criteria, the fraction of events with multiple D^* candidates is 8.6%. The D^0 candidate is selected from the list of candidates as the one having the smallest $\sum \chi_{K_S^0}^2$, where $\chi_{K_S^0}^2$ is associated with the K_S^0 vertex-constraint fit. In case this D^0 candidate is common to more than one D^* candidate, the candidate having the charged slow pion with the smallest transverse impact parameter is selected. The best candidate selection is found to select correctly the true candidate with an efficiency of 98%.

The MC-simulated events are used to investigate the sources of background for $D^0 \rightarrow K_S^0 K_S^0$ decays. The physics backgrounds, which are peaking in the ΔM distribution as the signal, are identified as specific physics process with same final state, $D^0 \rightarrow K_S^0 \pi^+ \pi^-$. Those are estimated directly from data using the K_S^0 mass sideband, $0.470 \text{ GeV}/c^2 < M_{\pi\pi} < 0.478 \text{ GeV}/c^2$ and $0.516 \text{ GeV}/c^2 < M_{\pi\pi} < 0.526 \text{ GeV}/c^2$.

The ΔM distributions for $D^0 \rightarrow K_S^0 \pi^0$ and $D^0 \rightarrow K_S^0 K_S^0$ are shown in Fig. 1. We describe the signal shapes by the sum of two symmetric and one asymmetric Gaussian functions with a common mean. Most of the shape parameters are fixed from MC, except for the mean and a width-calibration factor reflecting the possible MC-data difference. The peaking-background component has the same shape as the signal and its yield is fixed to the estimation described above. The background shapes are modeled with a threshold function: $f(x) = (x - m_\pi)^a \exp[-b(x - m_\pi)]$, where m_π is the nominal charged pion mass and a and b are shape parameters. The signal yield for $D^0 \rightarrow K_S^0 K_S^0$ is 5399 ± 87 events and for $D^0 \rightarrow K_S^0 \pi^0$ is 531807 ± 796 events.

A simultaneous fit of the ΔM for D^{*+} and D^{*-} is used (Fig. 2) to estimate the asymmetry. The signal and background shape parameters are common for both the particle and antiparticle. Both asymmetries in signal and background are allowed to vary in the fit. The A_{raw} for the peaking component in $D^0 \rightarrow K_S^0 K_S^0$ case (mostly due to $D \rightarrow K_S^0 \pi^+ \pi^-$) is fixed from the value obtained in data for the $D^0 \rightarrow K_S^0 \pi^0$ signal. The effect due to possible CP asymmetry in the $K_S^0 \pi^+ \pi^-$ and $K_S^0 \pi^0$ is accounted for as a systematic uncertainty. The A_{raw} observed in data for $D^0 \rightarrow K_S^0 K_S^0$ and $D^0 \rightarrow K_S^0 \pi^0$ is $(+0.45 \pm 1.53)\%$ and $(+0.16 \pm 0.14)\%$, respectively. This gives the time-integrated CP -violating asymmetry

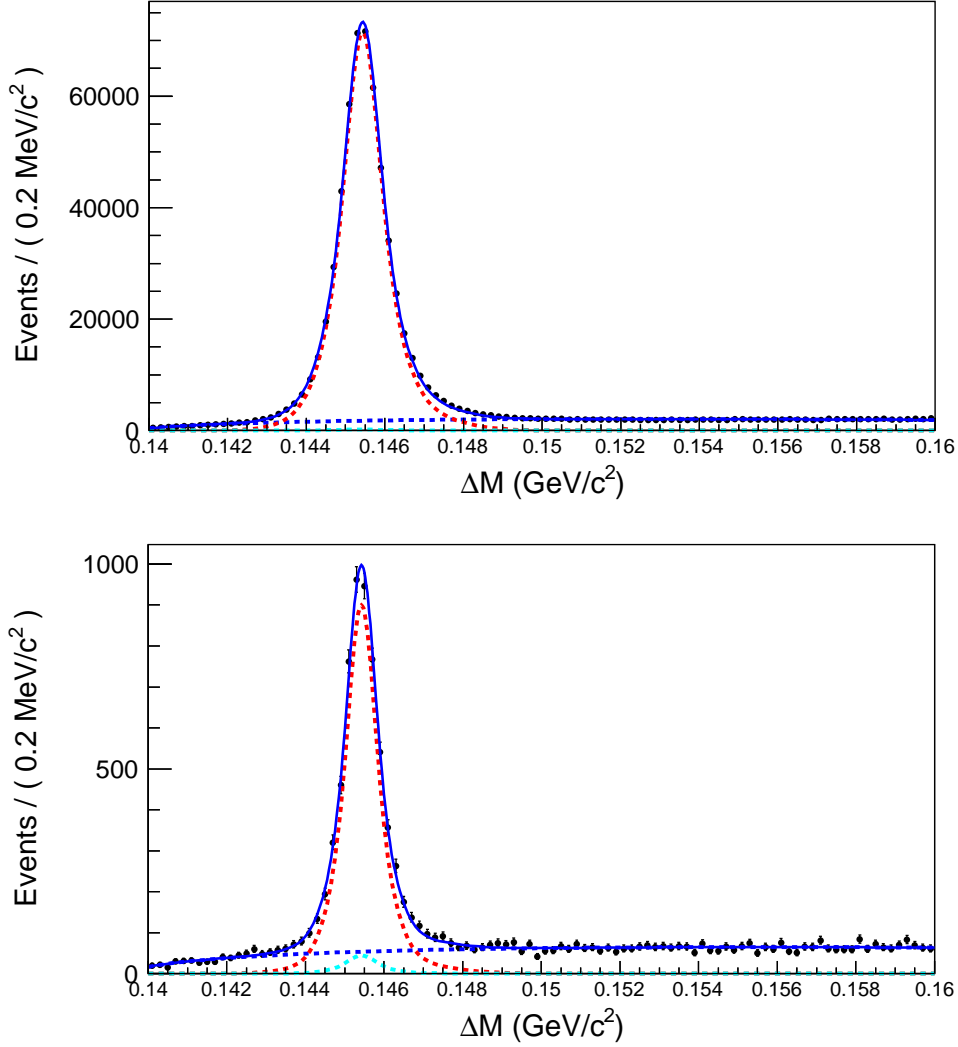


FIG. 1: Distributions of the mass difference ΔM for the $K_S^0 \pi^0$ (top) and $K_S^0 K_S^0$ (bottom) final states. Points with error bars are the data, the solid curves show the results of the fit, the dashed (blue) curves are the non-peaking background predictions and the dashed (cyan) curves are the peaking background.

A_{CP} , with only statistical error in the $D^0 \rightarrow K_S^0 K_S^0$ decay of

$$A_{CP} = (-0.02 \pm 1.53)\%$$

using a data sample of 921 fb^{-1} integrated luminosity.

The systematic uncertainties are summarized in Table I. We identify four sources of systematic uncertainty. The first is due to the uncertainties of the signal shapes: a systematic uncertainty is ascribed for each parameter determined and fixed from MC. We also vary the model by including an additional fudge factor that is allowed to vary. The peaking background yield is determined and fixed from the K_S^0 mass sideband. The fit procedure is repeated with its yield varied by its statistical uncertainty. We correct for a non-vanishing asymmetry originating from the different strong interaction of K^0 and \bar{K}^0 mesons with

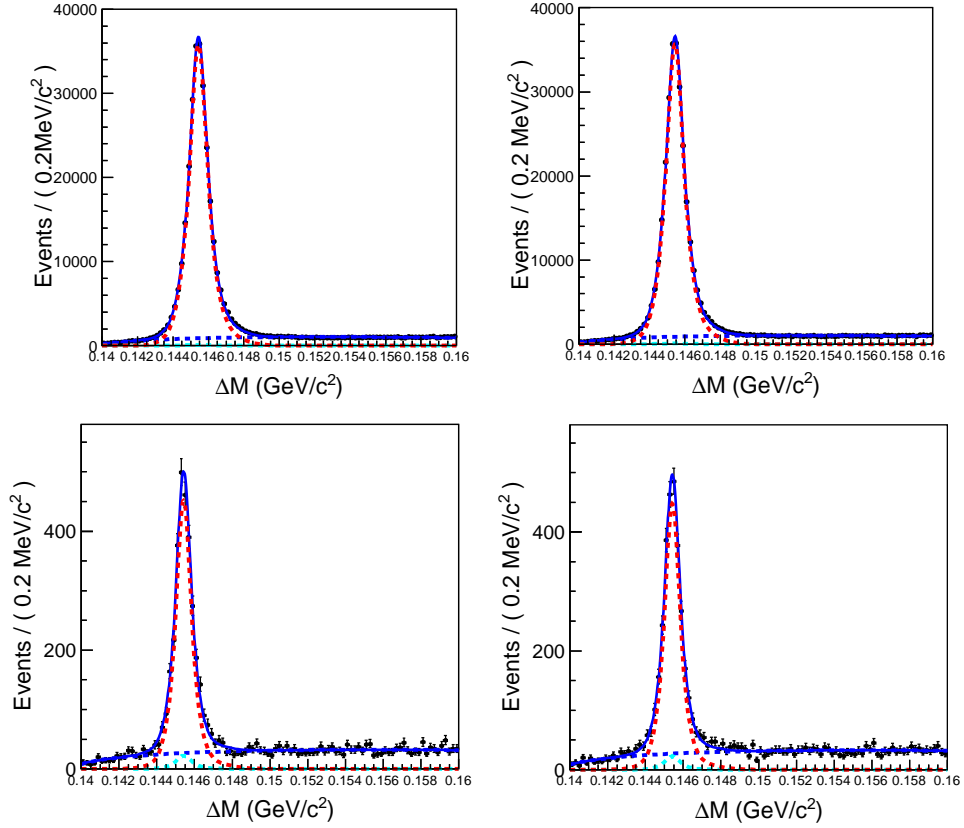


FIG. 2: Distributions of the mass difference ΔM for the $K_S^0 \pi^0$ (top) and $K_S^0 K_S^0$ (bottom). Left (right) plots are for the D^{*+} (D^{*-}) sample. Points with error bars are the data; the curves are explained in the caption of Fig. 1.

nucleons of the detector material, estimated to be -0.11% [11], and assign an additional systematic uncertainty of 0.01% . For the raw asymmetry, it is fixed from the $K_S^0 \pi^0$ measurement. The dominant systematic uncertainty comes from the uncertainty on the A_{CP} measurement of the normalization channel, $K_S^0 \pi^0$. Finally, we add these individual contributions in quadrature to obtain the total systematic uncertainty for the time-integrated CP -violating asymmetry A_{CP} in the $D^0 \rightarrow K_S^0 K_S^0$ decay of $\pm 0.17\%$.

| Source | Systematic uncertainty, in % |
|---------------------------------------|------------------------------|
| Signal shape | ± 0.01 |
| Peaking background | ± 0.01 |
| K^0/\bar{K}^0 material effects | ± 0.01 |
| A_{CP} measurement of $K_S^0 \pi^0$ | ± 0.17 |
| Total | ± 0.17 |

TABLE I: Summary of various sources of systematic uncertainties in $A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$.

In summary, we have measured the time-integrated CP -violating asymmetry A_{CP} in the $D^0 \rightarrow K_S^0 K_S^0$ decay of

$$A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\%$$

using a data sample of 921 fb^{-1} integrated luminosity. The dominant systematic uncertainty arises from the A_{CP} error of the normalisation channel. The result is consistent with the Standard Model expectation and is a significant improvement compared to the previous measurements of CLEO [6] and LHCb [7], already probing the region of interest for NP.

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